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THE X-15 PROGRAM

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Abstract

The X-15 has essentially attained its design performance in the flight research program accomplished to date.

The high-temperature structural design approach utilized for the X-15 configuration has been successful; no major design deficiencies were encountered nor major modifications required. With but few exceptions, the local thermal problems encountered have not affected primary structural areas.

In general, the aerodynamic derivatives extracted from flight-test data have confirmed the estimated derivatives obtained from wind-tunnel tests and thereby provided increased confidence in wind-tunnel evaluations at hypersonic speeds.

The aerodynamic flight control system and the simple stability augmentation system of the X-15 airplane have proved to be good technical designs. The airplane can be flown with satisfactory handling qualities through the range of dynamic pressures from about 1,500 lb/sq ft to below 100 lb/sq ft through the range of Mach numbers from about 6.0 to subsonic landing conditions.

Although only limited flight experience has been gained with the reaction-control system, its basic design appears to be completely adequate. This type of system apparently provides an adequate means of attitude control for future space vehicles. Pilot transition from aerodynamic controls to reaction controls has been accomplished without problems.

Reports from the X-15 pilots indicate that there are no piloting problems peculiar to the X-15 flight regime other than conventional pilot workload tasks.

Introduction

Since the first government flight in March 1960, the X-15 research program has been conducted in accordance with requirements for determining answers to the problems which the airplane was primarily built to study--aerodynamic and structural heating, hypersonic stability and control, control at low dynamic pressure, and piloting aspects. In addition, significant information, which was not considered to be of primary importance initially, has been derived relating to landing, aeromedical studies, simulation, and flight control systems. Other valuable data have been obtained on panel flutter, structural deformation, landing loads, structural effects on the stability augmentation system, engine nozzle erosion, and aerodynamic noise. This information was derived from several sources, including instrumentation of the X-15 airplane itself, postflight inspection of the X-15, medical data and commentary from the X-15 pilots, launch-airplane instrumentation and comments of the launch-airplane crew, comment of the escort-aircraft pilot and photography from the escort aircraft, and, on the ground, tracking, photography, and telemetry.

Flight Test Program

The X-15 was built with the objective of achieving a maximum velocity of at least 6,000 feet a second, an altitude of 250,000 feet, and a structural temperature of 1,200° F. Also, the airplane was constructed to be flown from launch through landing under direct control of the pilot. The validity of this approach has been verified by the successful progress of the research program. The maximum speed performance of the X-15 has been achieved at a Mach number of 6.04 (4,093 mph); an altitude of 246,000 feet has been exceeded; and a maximum temperature of 1,160° F has been obtained.

Shown in figure 1 is the performance capability of the X-15, including a shaded area which indicates the portion of the profile covered by flight test as of April 4, 1962. In addition, this performance envelope shows the relationship of dynamic pressure to altitude and velocity. As is apparent from the figure, the flight test dynamic-pressure has been intentionally limited to 1,500 lb/sq ft, thus allowing a margin for inadvertent overshoot.

Aerodynamic and Structural Heating

Heat-transfer data have been obtained on the X-15 in flight at speeds near free-stream Mach numbers of 3, 4, and 5, and at relatively low angles of attack. Turbulent heat-transfer methods were utilized and the results compared with X-15 flight data. The level of heat transfer predicted by reference-temperature methods is from 15 percent to 60 percent higher than the measured data, depending upon the assumed total-pressure level. Closer agreement with measured data has been obtained when the effective heating rate was neglected and attached-shock total-pressure levels were used.

Surface pressure and heat transfer which have been measured on the lower wing surface about midsemispan and on the lower fuselage centerline are shown in figure 2. In the upper part of the figure, measured pressures are compared with calculated pressures for the lower wing and lower fuselage. In the lower part of the figure, measured heat-transfer data are compared with calculated values. For the wing, the surface pressures are closely estimated by assuming an attached shock and expanded flow over the wing. Similarly good agreement is shown for the lower-fuselage centerline where a tangent-cone approximation has been used to calculate the local-pressure levels. Whether the approach shown by the solid line in this figure can be generalized depends largely on measurements of the actual total-pressure levels in flight over a range of skin heating rates.

Some evidence of the manner in which boundary-layer transition takes place on the airplane in flight has been determined by utilizing temperature-

sensitive paint. In figure 3 a plot of wing boundary-layer transition for a selected midsemi-span station on the wing is shown with a postflight temperature-sensitive-paint pattern. The correlation between the paint and calculated laminar and turbulent flow is illustrated on the plot. Illustrated also is the critical nature of the shift between laminar and turbulent flow. Results suggest the advisability of continuing to use conservative estimates for the transition location.

Maximum temperatures measured on the X-15 show that speeds in excess of a Mach number of 6 have been accomplished without extreme structural temperatures. Comparison of calculated and measured internal temperatures has shown that satisfactory thermal gradients through the structure can be predicted from known heat input to the exposed surfaces, as illustrated in figure 4. In general, the hot-structure concept used for the primary structure of the X-15 has proved to be quite satisfactory. Structural problems have developed during the flight program as a result of local hot spots and discontinuities in the structural elements. Many of these problems pertain to the X-15 only; however, thermal problems with windshield glass, airflow through openings in the external structure, and structural discontinuities can be expected to appear on all hypersonic vehicles until adequate design information is available in these problem areas.

Landing

Landings with the X-15 airplane have shown that the main-gear loads measured during the second reaction after nose-gear contact are several times larger than the loads experienced during the initial phase of the landing, as illustrated in figure 5. The large loads during the second main-gear reaction are attributed to the main-gear location as well as to the large tail loads, the negative wing lift, and the airplane inertial loads after nose-gear touchdown. The high nose-gear contact velocities caused by the airplane pitching down result in high nose-gear loads and, consequently, high accelerations on the pilot during this phase of the landing. Calculated results show that the main-gear reaction can be reduced by proper control of the elevator angle during touchdown. Theoretical results show that increasing the skid coefficient of friction reduces the main-gear reaction slightly, but increases the nose-gear reaction. The present gear system of the X-15 has proved to be adequate in general and has required very little attention.

Lift and Drag

Generally good agreement has been obtained between flight and wind-tunnel measurements of aerodynamic forces on the X-15 for the low angle-of-attack range covered. In the future, flights will be extended to higher angles of attack where interference and nonlinear effects are the predominant flow characteristics. Throughout the Mach number range considered, up to a Mach number of about 5, and in the low angle-of-attack range, wind-tunnel trim lift and drag obtained on models showed excellent agreement with flight results in the X-15. Furthermore, at least up to a Mach number of 3 and for the Reynolds number range greater than 5 million, flight data indicate that reasonable values of the full-scale minimum drag can be obtained from extrapolations of the wind-tunnel results to flight Reynolds numbers, provided the condition of the boundary layer is known and a representative wind-tunnel model is tested, even to the extent of including all of the protuberances found on a full-scale airplane. Existing theoretical methods were adequate for estimating the X-15 minimum drag. These theories, however, underestimate the drag due to lift and overestimate the maximum lift-drag ratio, primarily because of the inability of the theories to predict the control-surface deflections for trim. The two-dimensional theory which has been known to predict base pressure on relatively thin wings with blunt trailing edges also predicts satisfactorily the base pressure behind the extremely blunt vertical surface of the X-15.

Stability and Control

The X-15 flight program has established fairly well-defined derivative trends for Mach numbers approaching the design limit. With few exceptions, these trends have agreed well with the wind-tunnel predictions (fig. 6). Also, many of the basic stability and control design parameters have been confirmed as a substantial portion of the overall flight envelope. A gradual development of these basic trends from one flight to the next has, in fact, generated a high level of confidence in proceeding to the more critical flight areas during the past several months.

No serious flight control problems have been encountered in the longitudinal mode. However, one serious deficiency in the lateral-directional mode has been observed in the form of an adverse dihedral effect at high Mach numbers and angle of attack with the lower rudder on and the roll damper off. This problem was not revealed until the inputs of the pilot were used with the airplane stability to determine closed-loop stability. The serious implications of the lateral-directional control problem are illustrated in figure 7, which shows the range of angles of attack and Mach number in which the controllability problem is expected with the lower rudder on and the roll damper off. Flight trim limits of angle of attack plotted against Mach number and the uncontrollable or extremely difficult control areas are designated. Recovery from high-altitude flight will require penetration of this uncontrollable region and, thus, loss of roll damper during the critical portion of reentry would be a significant problem. Two means are available for improving the X-15 controllability with the roll damper off: reduction of angle of attack, which for an altitude reentry results in higher dynamic pressure and higher structural temperatures, or a special technique referred to as the $\dot{\beta}$-technique. This technique involves the use of manual aileron input to counteract the sideslip as indicated to the pilot. Although these special control techniques have not completely alleviated the problem, they have provided sufficient improvement, when the side stick is used, to allow flight in the fringes of the uncontrollable region. Removal of the lower rudder appears to be a promising means of alleviating the lateral-directional instability at high angles of attack. Finally, additional reliability has been obtained by dualization of certain components in the stability augmentation system. Further studies and tests are planned for the high Mach number and angle-of-attack ranges to reveal any further flight control problems that exist in these more critical areas and to fill out the remainder of the flight

envelope. In general, with the stability augmentation system functioning, the X-15 handles very well (much the same as century series fighters) and verifies that the established handling-qualities criteria for aerodynamic stability and control serve as good guidelines. Further quantitative information must be obtained on the performance of the attitude control rockets.

The third X-15 is equipped with a self-adaptive flight control system built by Minneapolis-Honeywell Regulator Co. A self-adaptive flight control system, as the name implies, monitors its own performance and adjusts its gains to provide essentially constant aircraft dynamics throughout the aircraft's flight envelope without benefit of air-data sensing or scheduling. Additional features of the system include integration of aerodynamic and reaction controls and autopilot hold modes in attitude and angle of attack.

It was found during development that the X-15 adaptive system was more sensitive to structural feedbacks than had been anticipated. Notch filters were installed to reduce system gain at primary structural frequencies. This modification, and other minor development changes, have resulted in average gain levels somewhat lower than had been anticipated. The flight demonstration is continuing satisfactorily, with the current objectives of decreasing reaction-control fuel consumption and increasing the usable angle-of-attack range.

Simulation

Pilot training procedures have proved to be adequate for a program of the X-15 type. The use of the analog simulator to establish pilot cues and timing and to allow the pilot to practice until the techniques become routine has considerably eased the total piloting task, thereby improving the pilot's ability to obtain precise flight data in the time available. Predictable emergency conditions or off-design missions have been encountered during the program and, in each instance, simulator training has contributed greatly to the pilot's ability to complete the mission. The two most valuable training devices have been a fixed-base six-degree-of-freedom analog simulator and the F-104 in-flight landing-pattern simulator. Other training devices such as the centrifuge and the variable-stability airplane have contributed to the overall pilot-experience level; however, they are not considered necessary for continuous use on a flight-by-flight basis. Expected problems, primarily in the area of aerodynamic heating, have also been encountered, but neither pilot nor flight vehicle safety has been compromised by the incremental-performance philosophy of envelope-expansion testing.

Operational Experience

Figure 8 presents a tabulation of the X-15 mission success as of November 1, 1961. In every instance, failures to achieve the planned performance were the result of powerplant and propellant system problems and pilot presentation deficiencies; stability augmentation and cabin pressure/pressure-suit systems problems contributed to the failures in achieving the prime mission objectives. Alternative modes of operation were available with which to obtain increased probability of mission success. For example, if the flow-direction-sensor ball nose failed after launch, a 2g pull-up could be performed until specified pitch angle was achieved. Reentry could be accomplished by reference to pitch on the attitude indicator, setting predetermined stabilizer angle, or reference to the horizon. However, all of these alternative procedures resulted in comparatively inaccurate flight profiles. Generous tolerances were allowed in performance when considering achievement of prime objectives. Even on several successful flights, there were problems similar to those noted.

A comprehensive evaluation of the X-15 flight operations, performed by Mr. R. G. Nagel of the AFFTC, has indicated that the program benefited greatly from inclusion of a pilot in the control loop and from redundant systems (figs. 9 and 10). These figures indicate the effects of pilot and redundancy upon the prelaunch and postlaunch phases of the X-15 operation. In figure 9 the total number of launches or attempts is shown for pilot plus redundancy in the actual case as compared to a hypothetical case for an unmanned vehicle with no redundancy, while for the postlaunch phase, the comparison in figure 10 includes the actual case of pilot plus redundancy and hypothetical cases of pilot only, redundancy only, and an unmanned vehicle with no redundancy. Note that the impact of pilot plus redundancy is more marked for free-flight operations than for prelaunch operations because of the prelaunch checkout procedure for detecting troubles.

A comparison with an independent evaluation of the Bomarc missile by the Boeing Co. is shown in figure 11. Whereas the unmanned X-15 is hypothetical, the manned Bomarc is hypothetical. The similarity of success and failure percentages is striking and serves to place further emphasis upon the value of the pilot in the system and of redundancy for increased success in other aerospace programs. It is significant that the pilot has been able to do the job, if not prevented by factors beyond his control, and recovered the airplane in all cases. Of course, the flights were planned for pilot operation, but the tasks were challenging, even so. The planning and execution of flights was generally successful and indicates that the initial concepts were correct. It is believed that even increased utilization of the pilot will be possible in advanced vehicles.

Physiological Data

To date, recorded physiological data from X-15 pilots have indicated only reasonably expected responses. Heart rates during flight have usually been from 140 to 150 beats per minute, about double the pilot's resting preflight heart rate. These levels have been confirmed by measurement of heart rates of 150 beats per minute during operational fighter landings. The data are useful, therefore, in establishing physiological baselines for pilots of high-performance vehicles.

Figure 12 presents flight time histories of altitude, velocity, normal and longitudinal acceleration, breathing rate, and heart rate as measured during an X-15 flight. One can see the general parallel response of breathing and heart rate to greater or reduced physical loading caused by maneuvering and thrust and drag. The heart rate is believed to be the more accurate indicator of work load, since breathing can be intentionally varied somewhat (by holding one's breath at high g, for example). Note that the last 4 minutes (time

400 sec to 630 sec) have the highest continuous heart rate, coincident with a steep descending turn with speed brakes extended, followed by pull-out and landing-pattern maneuvering. The anticipatory "spin-up" surges before launch and before descent, followed by decrease to required load, can also be seen.

Future X-15 Program

The X-15 program for the immediate future will be oriented toward continuing research investigations in the following primary areas: flight characteristics at high angle of attack; aerodynamic heating; reaction controls, including rate damping; adaptive control system; performance; displays; energy management; and bioastronautics. As these programs are completed, follow-on programs will explore some interesting new experiments such as ultraviolet stellar photography, infrared exhaust signature, landing computer, detachable high-temperature leading edges, horizon definition, and hypersonic propulsion.

Concluding Remarks

In reviewing the broad aspects of the accomplishments of the X-15 program, the following conclusions may be made:

The exploratory flight studies have indicated that hypersonic aerodynamic heating effects can be predicted with sufficient accuracy to support the design of a hot-structure vehicle such as the X-15 airplane. The high-temperature structural design approach utilized for this configuration has been successful; no major design deficiencies were encountered nor major modifications required. With but few exceptions, the local thermal problems encountered have not affected primary structural areas.

In general, the aerodynamic derivatives extracted from flight-test data have confirmed the estimated derivatives obtained from wind-tunnel tests and thereby provided increased confidence in wind-tunnel evaluations at hypersonic speeds.

The aerodynamic flight control system and the simple stability augmentation system of the X-15 airplane have proved to be good technical designs. The airplane can be flown with satisfactory handling qualities through the range of dynamic pressures from above 1,500 lb/sq ft to below 100 lb/sq ft through the range of Mach numbers from about 6.0 to subsonic landing conditions.

Although only limited flight experience has been gained with the reaction-control system, its basic design appears to be completely adequate. This type of system apparently provides an adequate means of attitude control for future space vehicles. Pilot transition from aerodynamic controls to reaction controls has been accomplished without problems.

Reports from the X-15 pilots indicate that there are no piloting problems peculiar to the X-15 flight regime other than conventional pilot workload tasks.

Symbols

a_n	normal acceleration, g units
a_x	longitudinal acceleration, g units
C_{l_β}	effective dihedral derivative
C_{m_α}	longitudinal stability derivative
C_{N_α}	slope of airplane normal-force-coefficient curve
C_{n_β}	directional stability derivative
g	acceleration due to gravity, ft/sec^2
H	altitude, ft
h	heat-transfer coefficient, $\frac{\text{Btu}}{\text{ft}^2\text{-}^\circ\text{F-sec}}$
M	Mach number
N_{Pr}	Prandtl number
p	pressure
$p_{t,A}$	attached-shock total pressure
$p_{t,N}$	total pressure behind normal shock
$p_{t,\infty}$	free-stream total pressure
q	dynamic pressure, psf
T_R	boundary-layer recovery temperature, $T_R = T_l\left(1 + \frac{\gamma - 1}{2}\eta M_l^2\right)$
T^*	reference temperature, $T^* = T_l + 0.5\left(T_W - T_l\right) + 0.22\left(T_R - T_l\right)$
$(T^*)_{aw}$	adiabatic-wall reference temperature, $(T^*)_{aw} = T_l + 0.72\left(T_R - T_l\right)$
V	velocity, ft/sec
V_{v_0}	airplane sinking speed at initial touchdown, ft/sec
W	airplane landing weight, lb
x_f	length from fuselage nose, ft
x_w	length from wing leading edge, ft
α	angle of attack, deg
α_0	initial angle of attack at touchdown, deg
γ	ratio of specific heats
δ_h	horizontal-stabilizer position, deg
η	recovery of factor $\left(\sqrt{N_{Pr}}\right.$ for laminar flow, $\left.\sqrt[3]{N_{Pr}}\right.$ for turbulent flow$\left.\right)$

Subscripts:

l	local
W	wall or skin

X-15 PERFORMANCE ENVELOPE

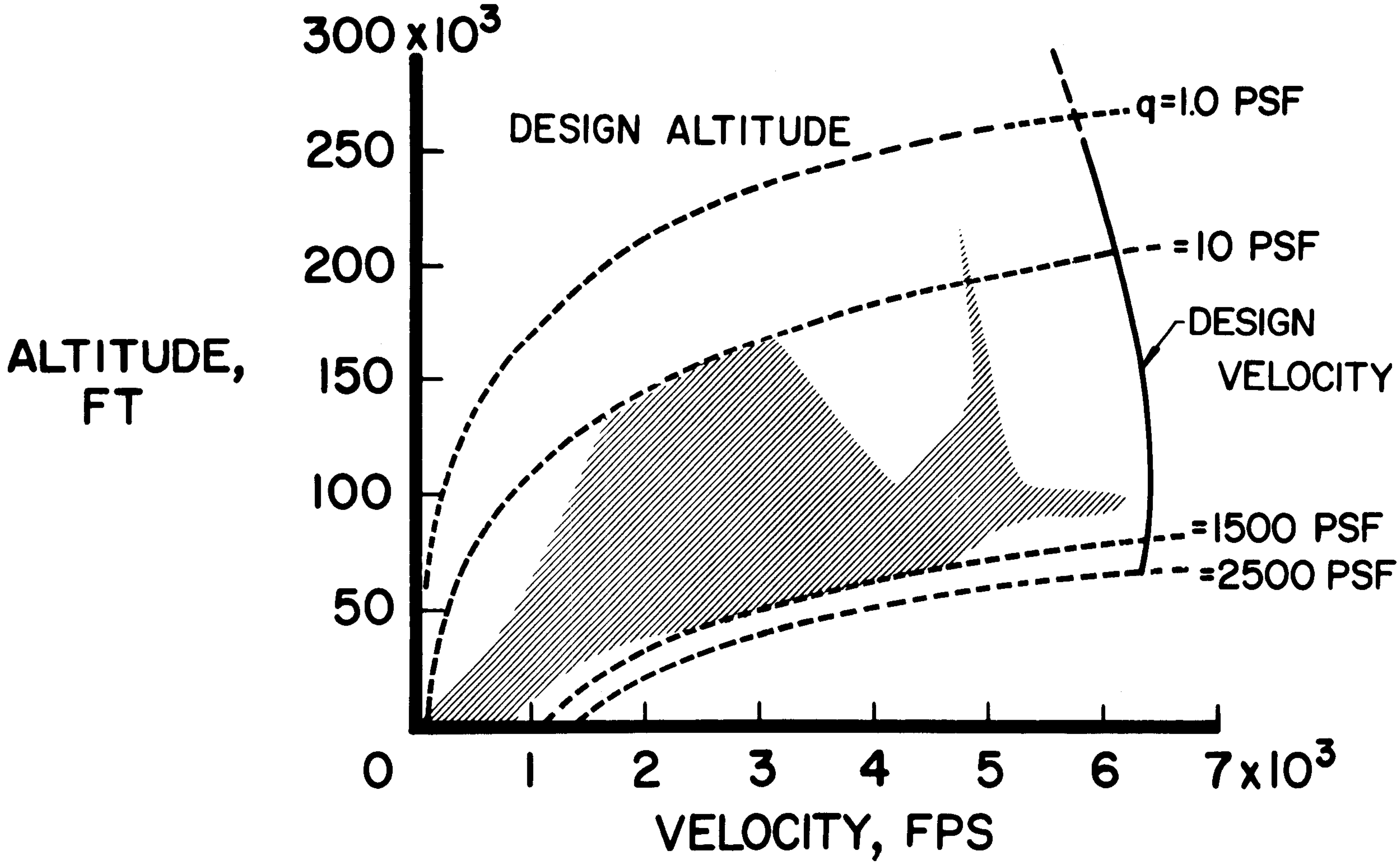


Figure 1

SURFACE PRESSURES AND HEAT TRANSFER

$\alpha \approx 4$

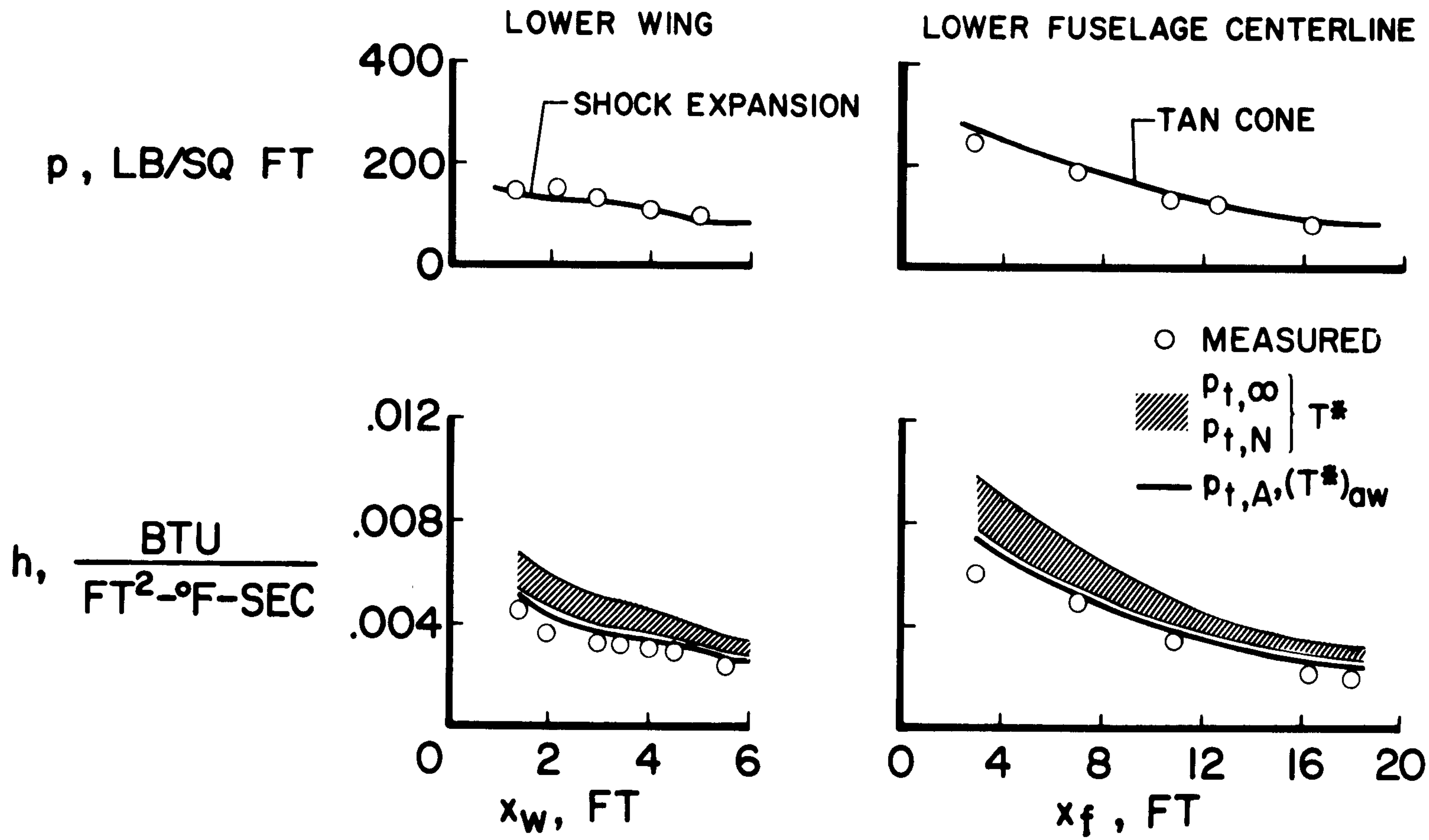


Figure 2

WING BOUNDARY-LAYER TRANSITION

$\alpha \approx 4$

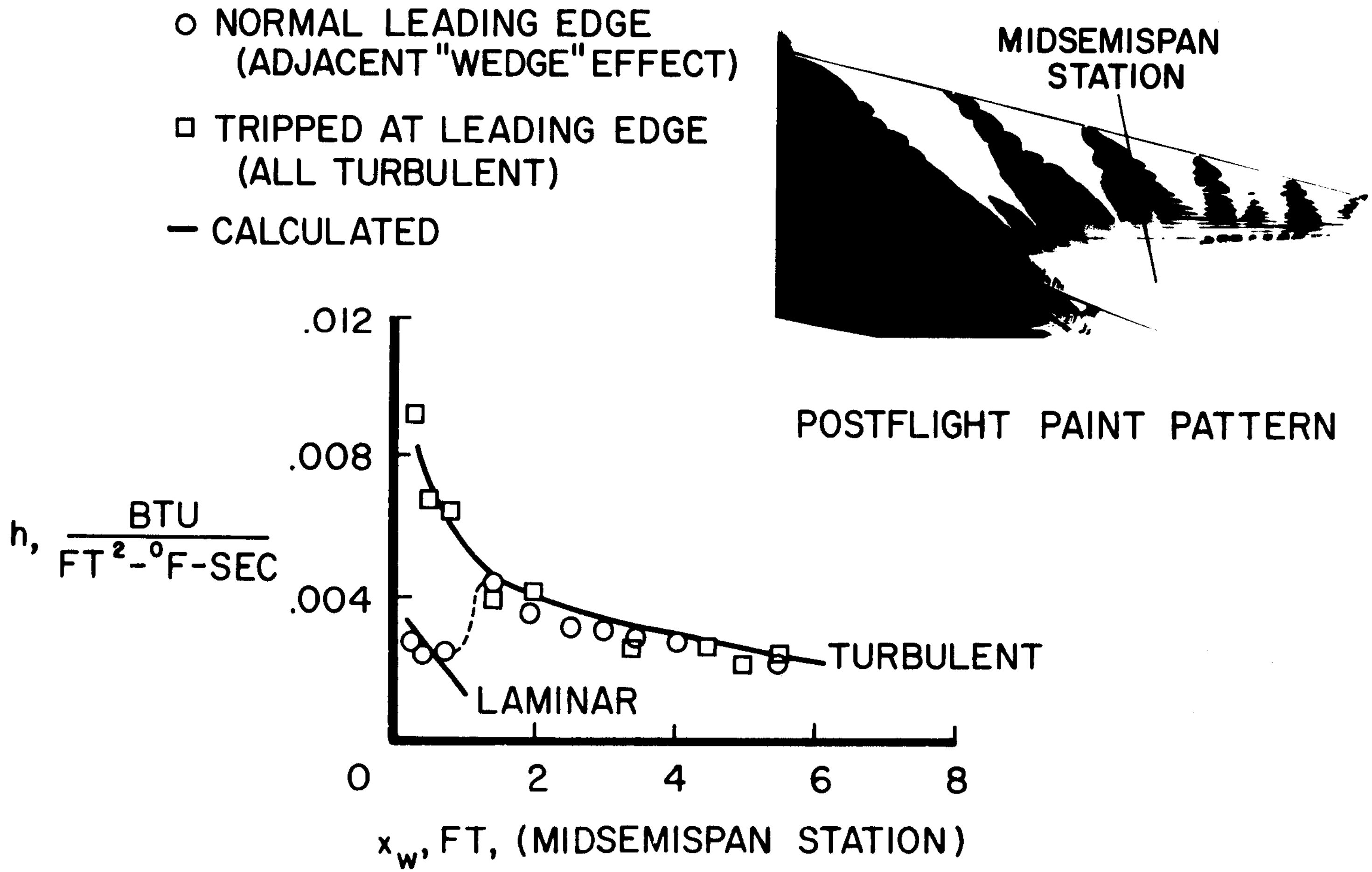


Figure 3

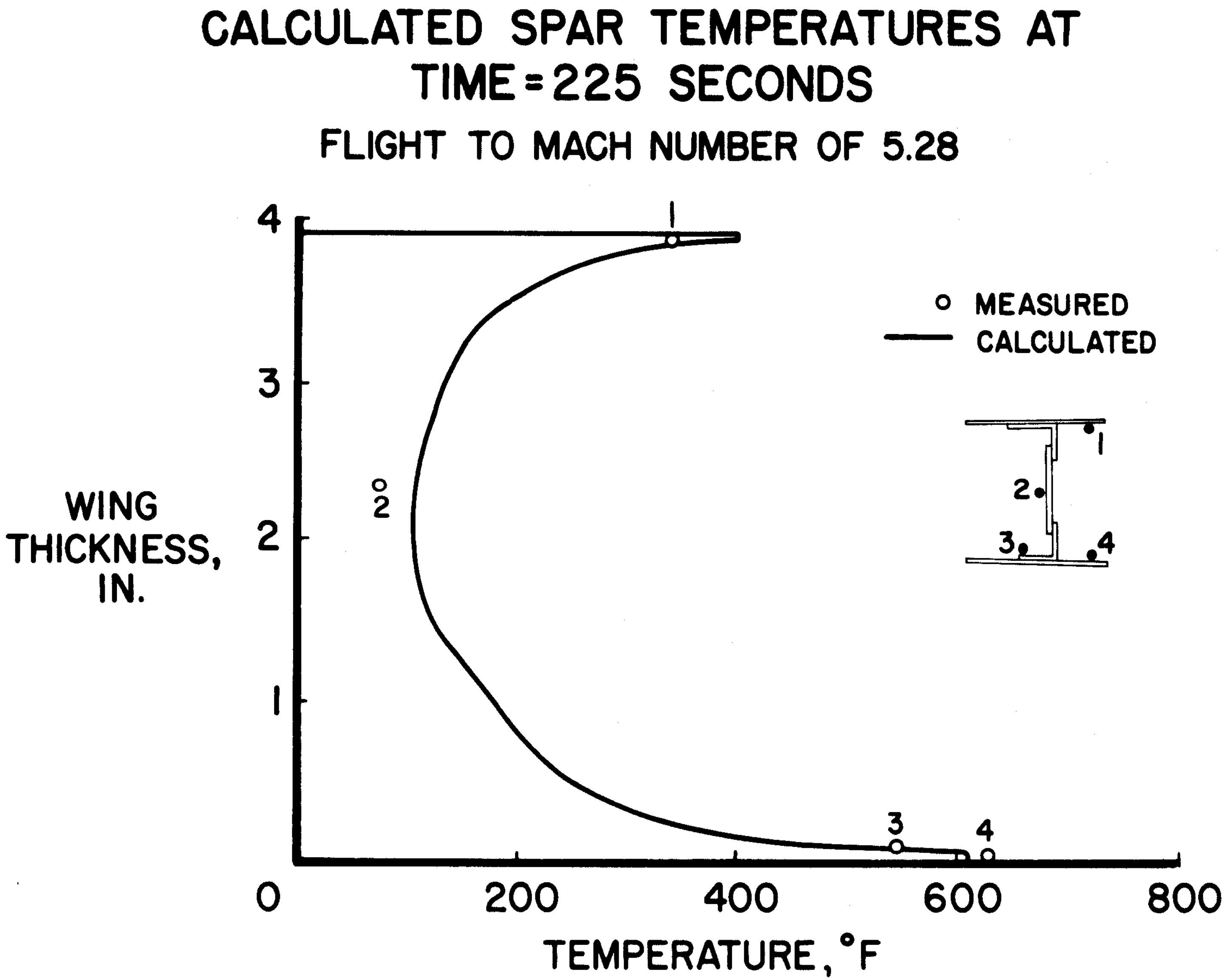

CALCULATED SPAR TEMPERATURES AT
TIME = 225 SECONDS
FLIGHT TO MACH NUMBER OF 5.28
MEASURED
CALCULATED
WING THICKNESS, IN.
TEMPERATURE, °F
0
200
400
600
800
1
2
3
4

Figure 4

MAIN-GEAR-SKID VERTICAL REACTION

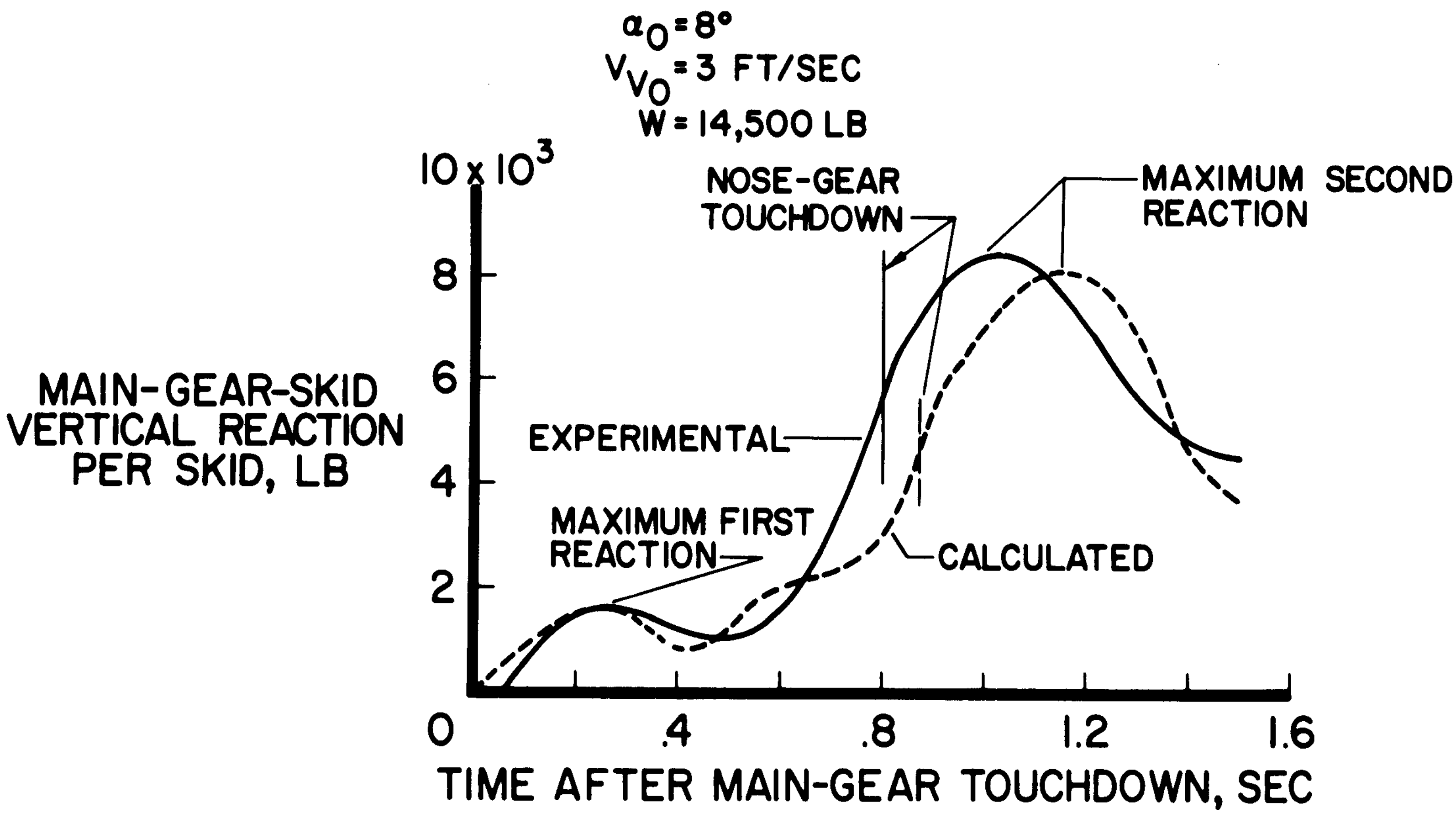


Figure 5

X-15 STABILITY DERIVATIVES

$2° < \alpha < 6°$

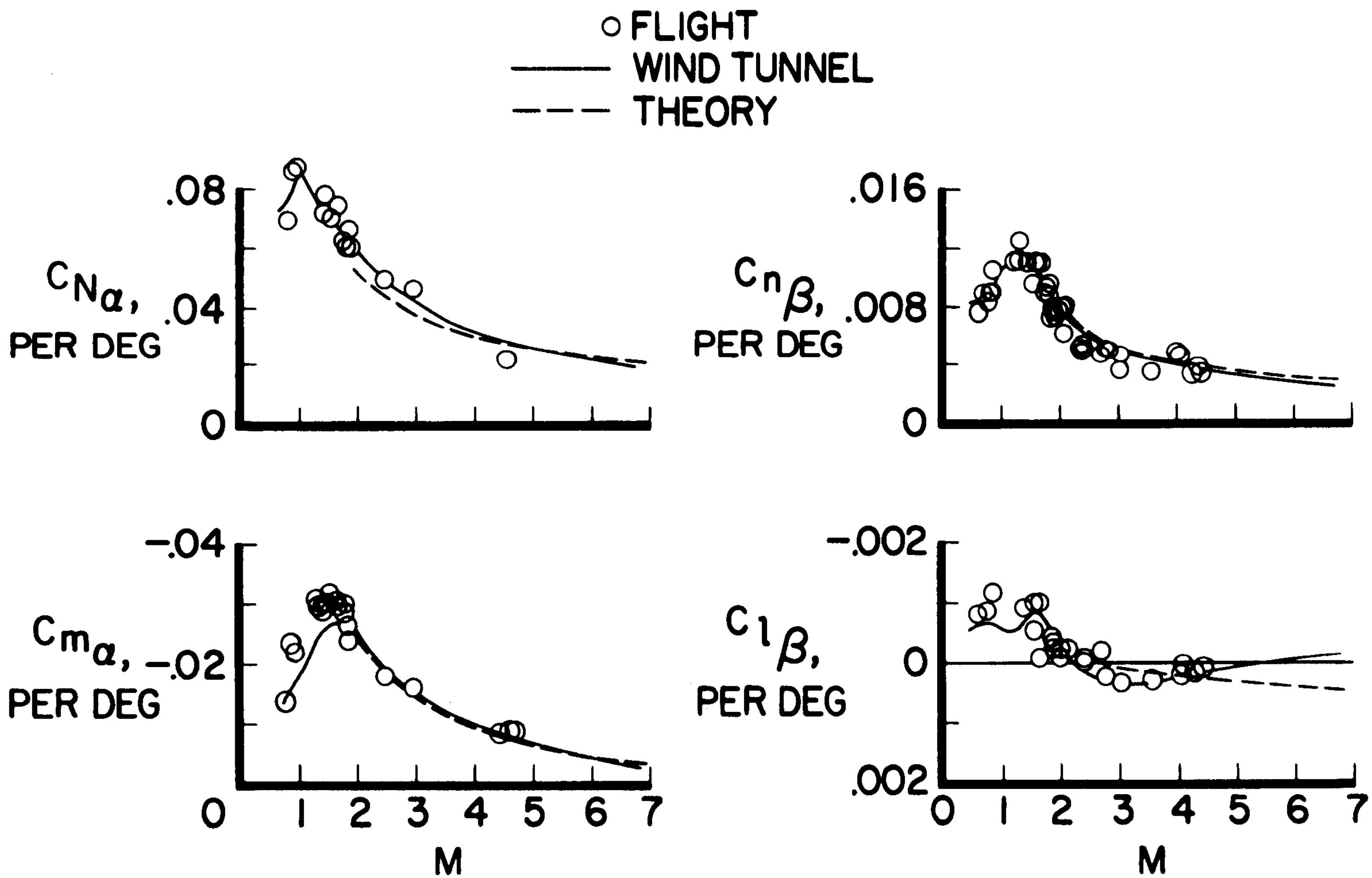


Figure 6

SUMMARY OF PREDICTED STABILITY AND CONTROL

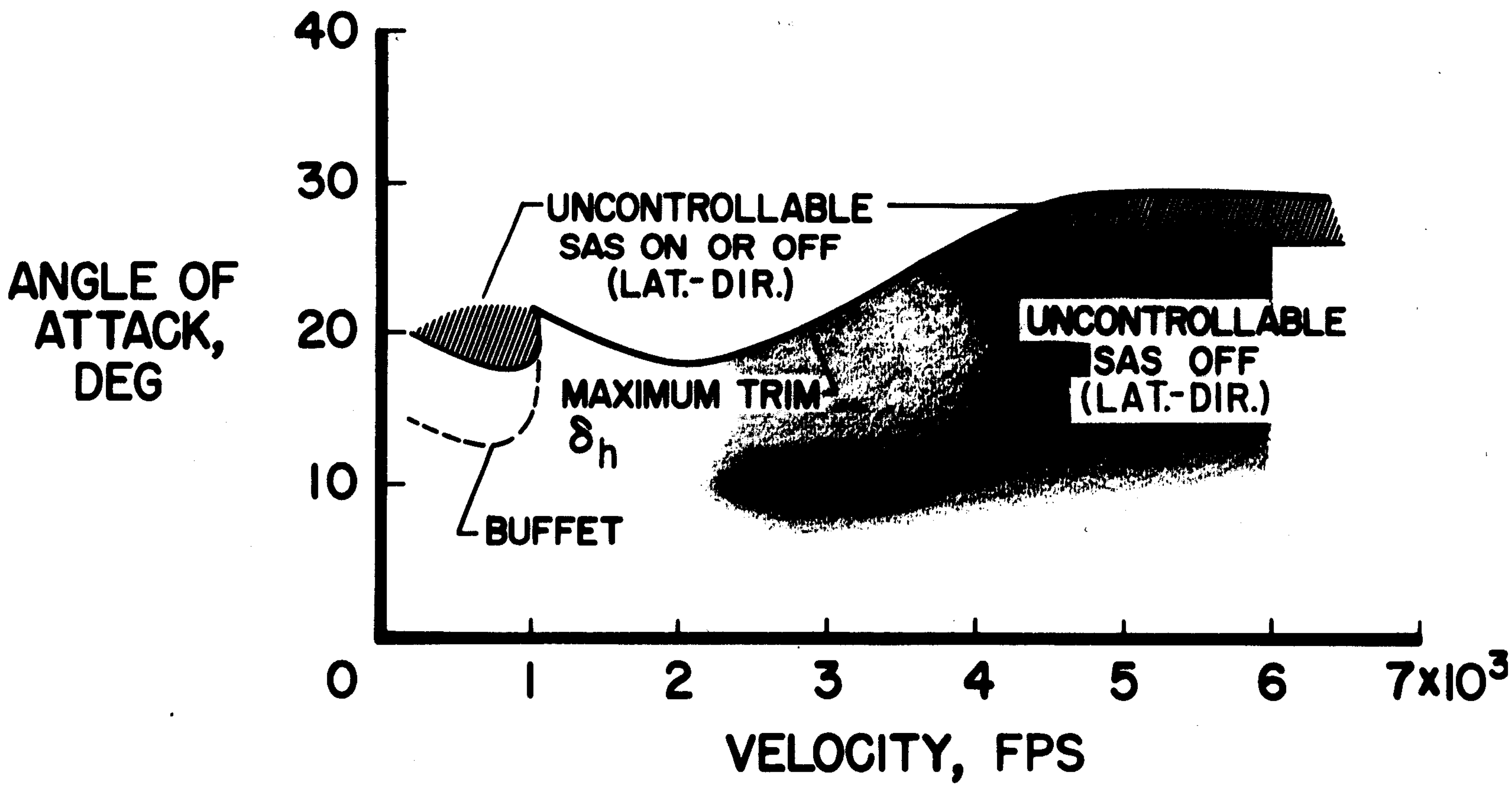


Figure 7

X-15 FLIGHT SUMMARY

AS OF NOVEMBER 1, 1961

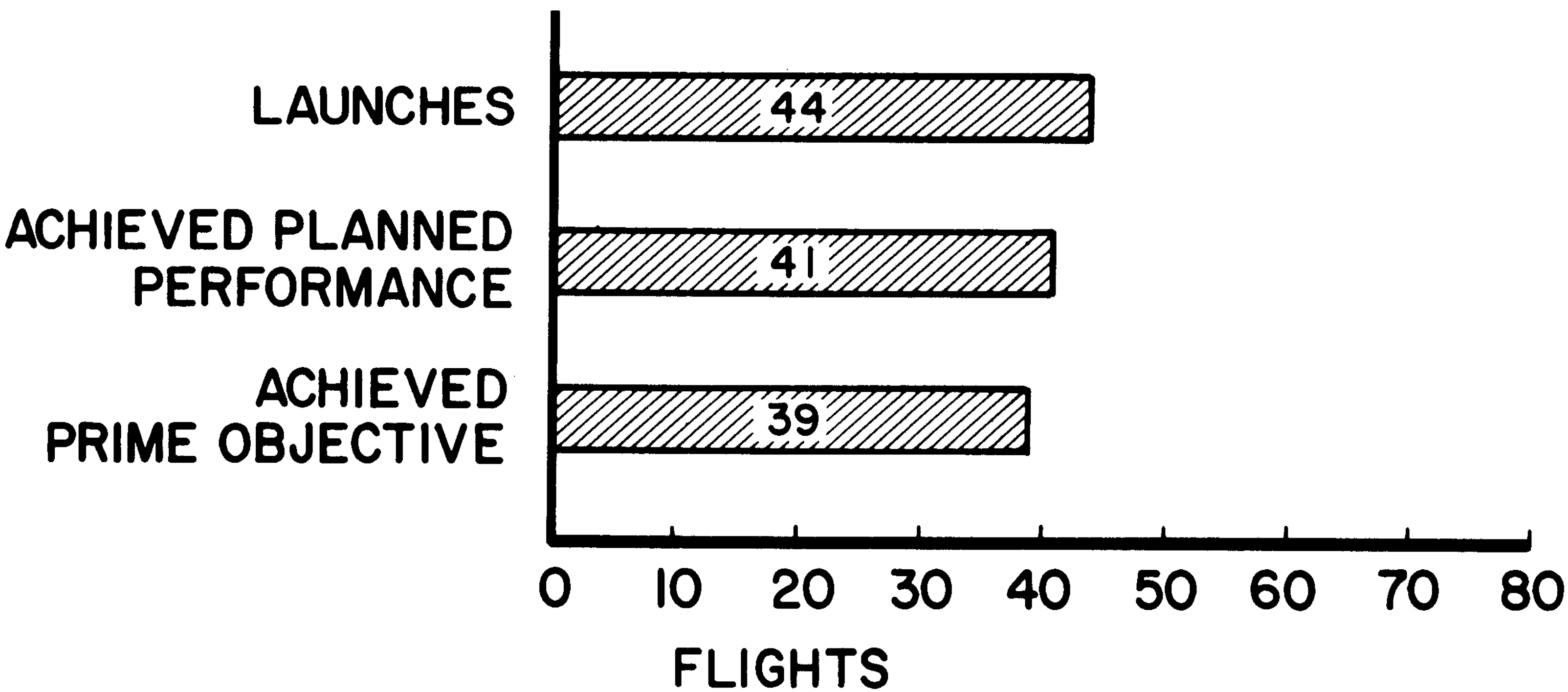


Figure 8

OVERALL PILOT-IN-THE-LOOP AND REDUNDANCY BENEFITS

PRE-LAUNCH + POST-LAUNCH

(THROUGH NOV. 1, 1961)

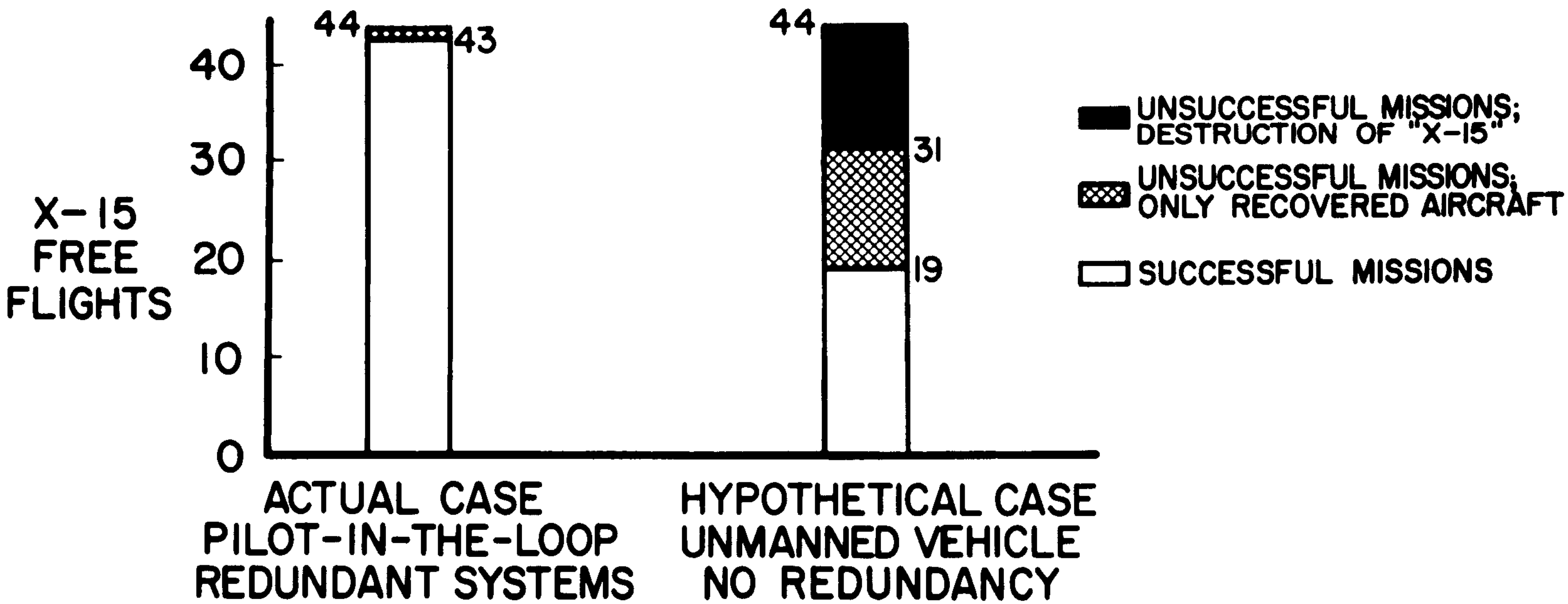


Figure 9

QUANTITATIVE SUMMARY OF X-15 FREE FLIGHTS

POST-LAUNCH PHASE

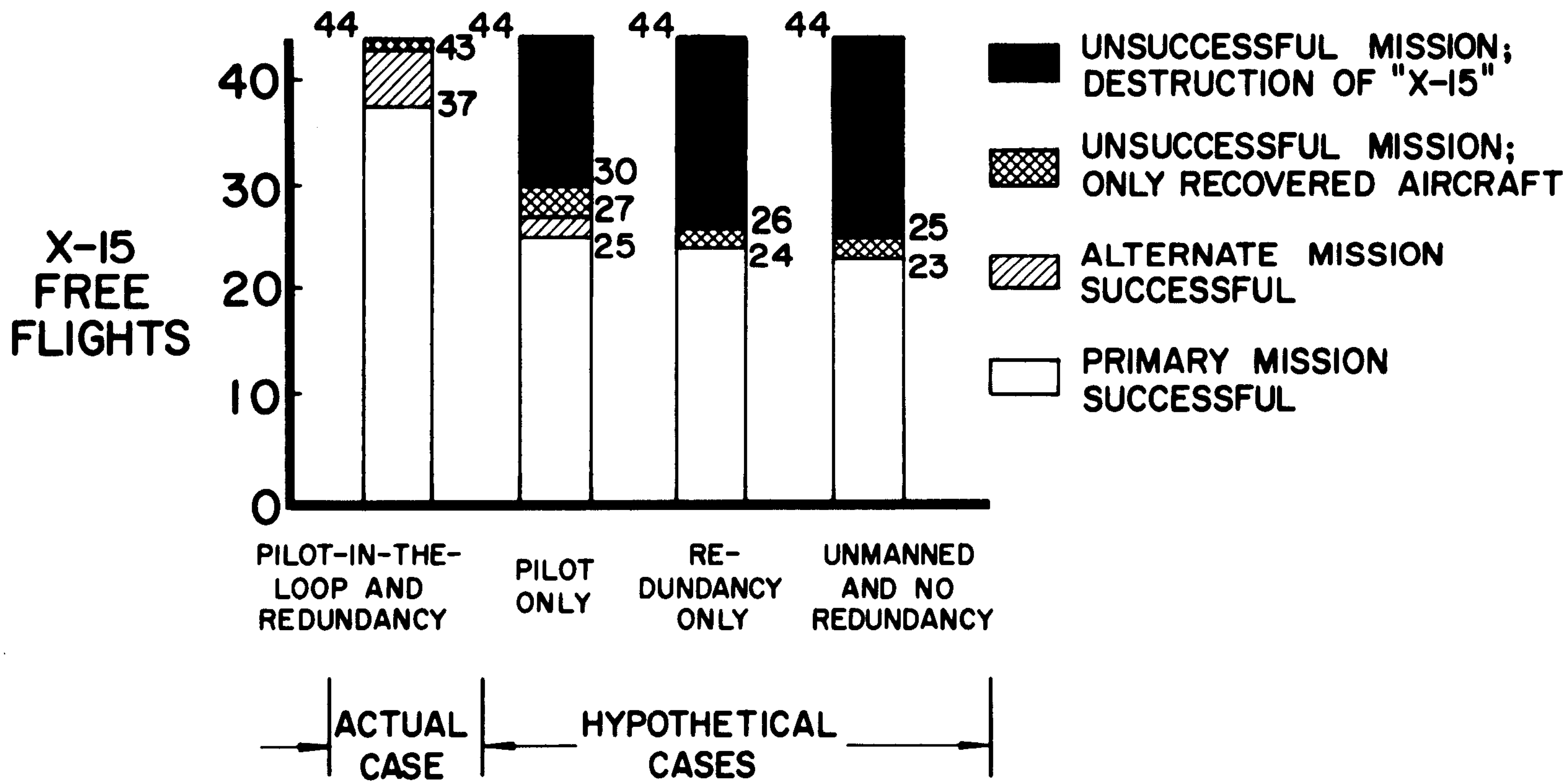
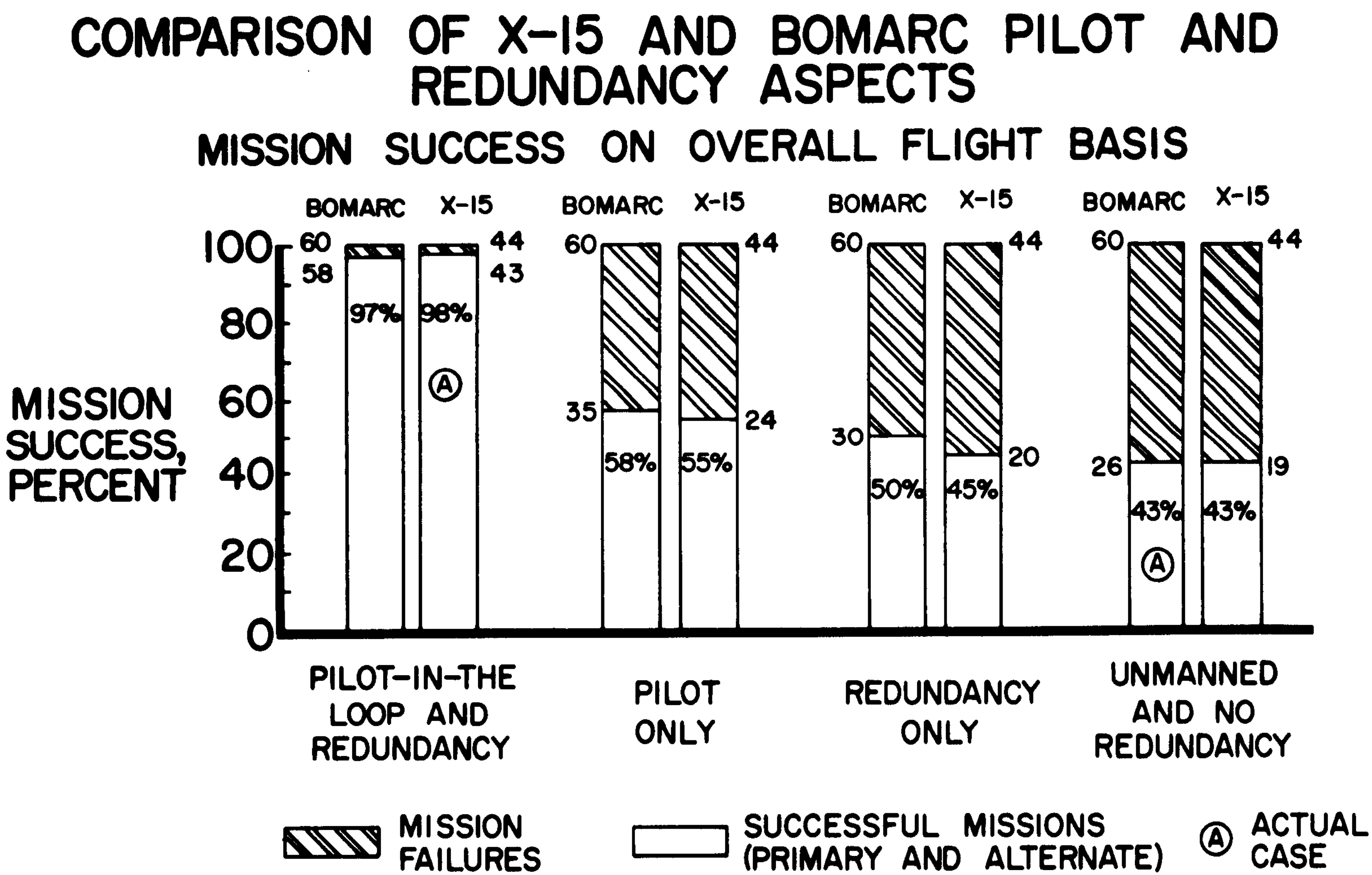


Figure 10



COMPARISON OF X-15 AND BOMARC PILOT AND REDUNDANCY ASPECTS
MISSION SUCCESS ON OVERALL FLIGHT BASIS
BOMARC
X-15
MISSION SUCCESS, PERCENT
100
80
60
40
20
0
60
58
44
43
97%
98%
A
35
24
58%
55%
30
20
50%
45%
26
19
43%
43%
PILOT-IN-THE LOOP AND REDUNDANCY
PILOT ONLY
REDUNDANCY ONLY
UNMANNED AND NO REDUNDANCY
MISSION FAILURES
SUCCESSFUL MISSIONS (PRIMARY AND ALTERNATE)
A ACTUAL CASE

Figure 11

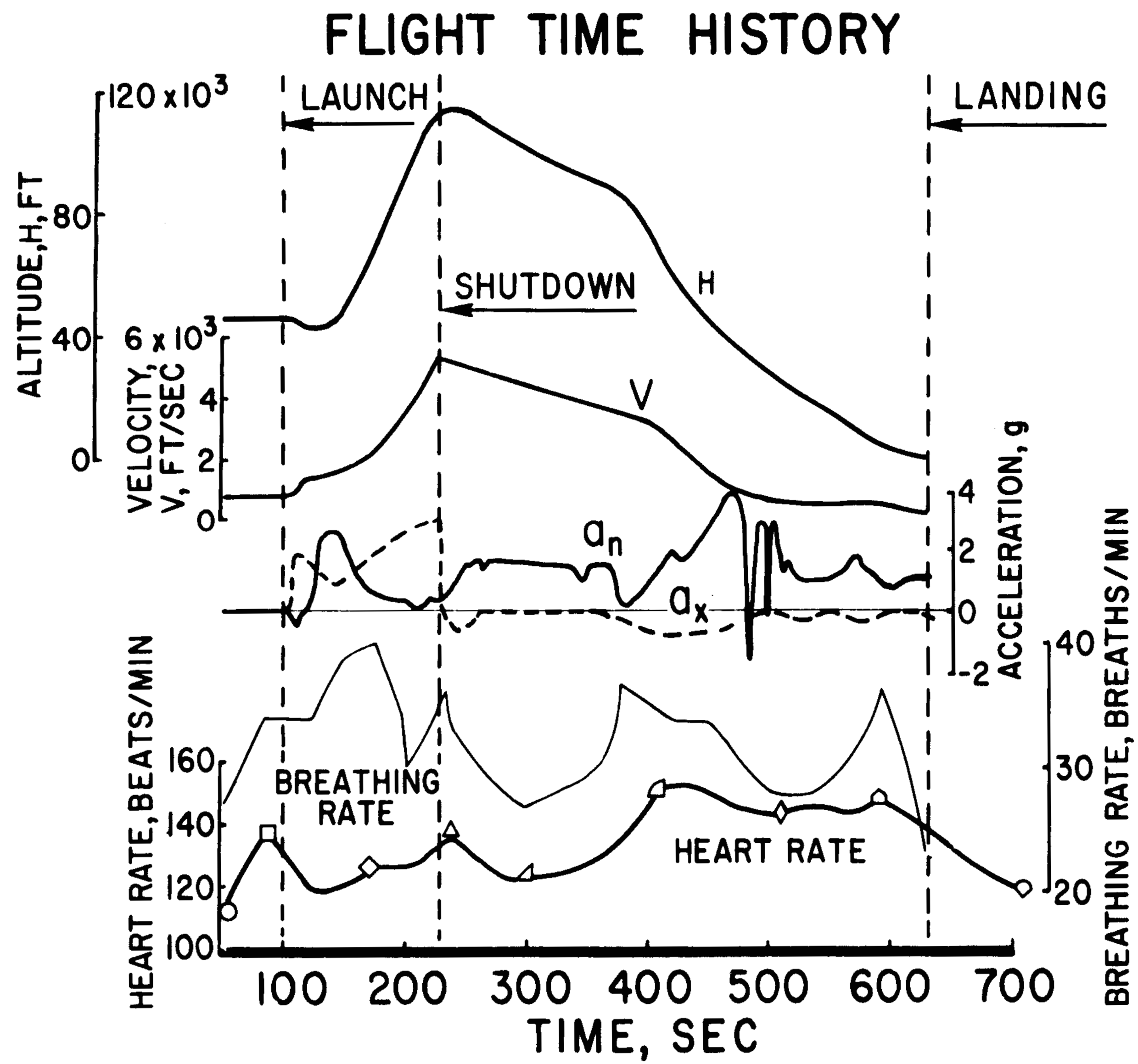

FLIGHT TIME HISTORY
120 x 10^3
LAUNCH
LANDING
ALTITUDE, H, FT
80
40
0
SHUTDOWN
H
VELOCITY, V, FT/SEC
6 x 10^3
4
2
0
V
ACCELERATION, g
4
2
0
-2
a_n
a_x
HEART RATE, BEATS/MIN
160
140
120
100
BREATHING RATE
HEART RATE
BREATHING RATE, BREATHS/MIN
40
30
20
100
200
300
400
500
600
700
TIME, SEC

Figure 12